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Development of a Power Electronics Unit for the Space Station Plasma Contactor

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ABSTRACT

A hollow cathode plasma contactor has been baselined as a charge control device for Space Station (SS) to prevent deleterious interactions of coated structural components with the ambient plasma. NASA Lewis Research Center Work Package 4 initiated the development of a plasma contactor system comprised of a Power Electronics Unit (PEU), an Expellant Management Unit (EMU), a command and data interface, and a Plasma Contactor Unit (PCU). A breadboard PEU was designed and fabricated, and contained a cathode heater and discharge power supply, which were required to operate the PCU, a control and auxiliary power converter, an EMU interface, a command and telemetry interface, and a controller. The cathode heater and discharge supplies utilized a push-pull topology with a switching frequency of 20 kHz and pulse-width-modulated (PWM) control. A pulse ignition circuit derived from that used in arcjet power processors was incorporated in the discharge supply for discharge ignition. An 8088 based microcontroller was utilized in the breadboard model to provide a flexible platform for controller development with a simple command/data interface incorporating a direct connection to SS Multiplexer/Demultiplexer (MDM) analog and digital I/O cards. Incorporating this in the flight model would eliminate the hardware and software overhead associated with a 1553 serial interface. The PEU autonomously operated the plasma contactor based on command inputs and was successfully integrated with a prototype plasma contactor unit, demonstrating reliable ignition of the discharge and steady-state operation.

INTRODUCTION

High voltage solar arrays which typically operate at 140 to 160 VDC output have been baselined for the Space Station (SS) power system. The power system is configured with a negative ground, which ties the negative output of the solar arrays to the vehicle structure. Exposed conducting surfaces on the solar arrays provide a large surface area for electron collection from the surrounding space plasma. The negative system ground places all of these exposed solar array surfaces at a potential above the structural components and habitation modules. All of these structural components have electrically insulating surface treatments. This combination allows the structure and habitation modules to float at potentials as large as -120 V with respect to the ambient plasma.[1] This large potential difference can produce deleterious interactions, which include spontaneous and debris induced arcing and sputtering between the space plasma and the coated surfaces. This can result in degradation of the coatings, deposition of sputtered material on sensitive surfaces, and electromagnetic interference (EMI). A plasma contactor was selected to alleviate the potential difference between SS structures and the space plasma. NASA Lewis Research Center Work Package 4 was directed to begin the plasma contactor development program.[2]

A hollow cathode plasma source was chosen for the plasma contactor unit based on its demonstrated low impedance, high current capability, and self-regulating emission control mode. Hollow cathodes are also widely recognized as the optimal charge control concept by the spacecraft-charging community.[3-5] Hollow cathodes have also flown as components of ion propulsion and spacecraft charging systems.[6-10] The hollow cathode plasma contactor operates by ionizing an expellant gas in a discharge between the hollow cathode and a local anode. This ionized gas then acts as a plasma bridge between the hollow cathode and the ambient plasma, allowing electrons to be emitted from the hollow cathode into the ambient plasma, thereby discharging the spacecraft. The electron emission process is self-regulating, requiring no outside control. The details of the SS plasma contactor are explained in a companion paper.[11]

The operation of the plasma contactor requires a power supply to drive a resistance heater which is used to elevate the cathode insert temperature to facilitate electron emission. A second power supply is used to initiate and maintain the discharge between the cathode and local anode. Xenon gas is provided to the hollow cathode by the Expellant Management Unit (EMU). The power supplies must be set at appropriate power levels and sequenced properly with the EMU to ensure proper operation of the hollow cathode. An autonomous Power Electronics Unit (PEU) was developed to operate the plasma contactor. The PEU contained all power supplies required for both plasma contactor and EMU operation. A single board microprocessor based controller operated the plasma contactor system based on command inputs. Under this pre-flight development program, the PEU hardware will brought to a breadboard level and will demonstrate compatibility with an engineering model PCU under lifetest conditions simulating all flight modes. The PCU load dynamics will be fully characterized to generate interface specifications for the PEU and control laws for PCU fault detection and resolution will be developed and verified. These specifications, and breadboard PEU hardware, will be provided to the flight contractor to assist in the development of flight hardware. This paper documents the overall design of the plasma contactor PEU.

SYSTEM OVERVIEW

The plasma contactor system will be contained in an orbital replacement unit (ORU) avionics box, and a simplified layout is shown in Figure 1. This box is a standard Space Station fixture which provides thermal, structural, data, and power interfaces and accommodates robotic installation. The plasma contactor system consists of the hollow cathode plasma contactor unit (PCU); the expellant management unit (EMU) consisting of a xenon storage tank, pressure regulator and sensors, and all valves and tubing; and the power electronics unit (PEU). The PEU consists of the power supplies necessary to run the plasma contactor and provide housekeeping power, the EMU interface, and the controller. A block diagram of the PEU is shown in Figure 2. To satisfy single fault tolerant requirements, two complete plasma contactor systems will be present on the space station at all times with one operational unit and one backup unit. In the event of a failure, the backup system will be activated and the defective unit replaced.

PEU OVERVIEW

Power from the 120 VDC SS bus is brought into the PEU through an electromagnetic interference (EMI) filter to minimize conducted EMI from the PEU. At the time of this writing, the EMI filter has not yet been designed. The control power and auxiliary power converters are energized when power is applied to the ORU box. The control power converter provides +/- 15 VDC control power throughout the PEU. The controller is also immediately powered up and resets itself and the PEU to a standby state, until a command is received from the command / telemetry interface. The Auxiliary Power Converter (APC) provides a 28 VDC, 50 W bus which is used by the EMU pressure transducers and valves, and the controller. The cathode heater and main discharge supplies provide power to the PCU. Detailed functional requirements for each unit are covered in a later section.

Control Power Converter

The control power converter provides +/- 15 VDC, 30 W maximum power for control purposes throughout the PEU. For this reason, it is essential for this converter to power up immediately when power is applied to the PEU. The power converter used for this purpose is a space-rated commercially available unit that provides a maximum of 30 W of power, which exceeds the maximum requirements of the PEU.

Auxiliary Power Converter

The auxiliary power converter provides a 28 VDC, 50 W bus for use in the EMU for valve drive, pressure transducer excitation, and xenon tank heating. This converter is also a commercially available unit with appropriate qualifications for space application.

Cathode Heater Supply

The cathode heater supply conditions power from the main power bus and provides a constant current DC output to the cathode heater. The power supply is used for the activation and ignition modes of contactor operation. These modes are described in detail in a later section. The power supply has a low current setpoint used in the activation process, a nominal setpoint used in the activation process and ignition preheat, and a high current setpoint used in the event of ignition difficulties. The setpoints and on / off commands are selected by the controller based on the mode of operation. The actual value of the setpoints are being determined in the PCU development process.

The cathode heater used in the PCU is derived from the heater design for the NASA 30 cm ion thruster, and is a life test program is underway to develop it to engineering model status.[10] This heater has a room temperature resistance of approximately 0.3 Ω, increasing to 1 - 1.2 Ω at nominal operating temperature. The power supply must provide a maximum of 12 A through this load with < 10 % current ripple and 1 % line / load regulation. This maximum current is larger than presently felt required, but was selected to ensure that ample power is available.

Anode Supply

The anode supply must reliably ignite and maintain the PCU cathode-anode discharge. Ignition is accomplished by application of the open circuit voltage to the heated cathode. If ignition does not occur with the open circuit voltage, a series of high-voltage pulses is applied to the anode. This ignition technique has been previously demonstrated with a flight arcjet system without adversely affecting system / spacecraft EMI compatibility.[12] The anode supply is a single-setpoint, 2 ampere, constant current output power supply with the on / off commands for the power supply and the high voltage pulser provided by the controller. The pulser and cathode heater supply are automatically disabled when the discharge ignites.

The anode supply also accommodates the measurement of the PCU emission currents. This is accomplished via a current sensor which will monitor the return current passing through a ground strap between the PCU and SS single point ground, as shown in Figure 2. As there will be no plasma diagnostics package aboard SS, these data will be of value in establishing collateral evidence of SS potential control.

Controller

The controller selected for the breadboard PEU development is an 8088 based single board computer with analog and digital input / output capability. A block diagram of the controller appears in Figure 3. This level of complexity exceeds the needs of the plasma contactor system, but permits a high degree of flexibility in the PEU development process. The flight type controller would likely be a sequential logic device. The controller takes commands input from the SS Data Management System (DMS) interface and sequences the power supplies associated with PCU operation and the valves for the EMU. All analog sensor data are processed by the controller internally for error trapping and fault recovery purposes. These data are also passed through directly to the DMS interface.The controller responds to contactor on and off commands, and a cathode activation command. The details of controller operation are described in the next section.

CONTROLLER FUNCTIONAL REQUIREMENTS

Command and Telemetry Interface

The controller must process commands received from the SS DMS and transfer telemetry data to the DMS. The present scheme involves a direct connection between a Multiplexer / Demultiplexer (MDM) unit and the PEU via MDM analog and digital I / O cards. This command / telemetry interface selection was chosen to maintain simplicity in the power electronics and to take advantage of the DMS standard services of analog / digital I/O. This eliminated the need for a local 1553 bus interface and the associated hardware and software overhead. As previously stated, the PEU receives contactor on, contactor off, and cathode activation commands from the DMS. To accomplish this, two parallel lines are brought from the MDM with command data. An additional line provides a latching signal that latches the command into the PEU command input register. Analog telemetry data are passed through the controller to the MDM for digitization and insertion into the SS data stream. This interface configuration is a candidate for the flight system. The command and telemetry lists are summarized in Tables I and II respectively.

Power Supply Control

The control power and auxiliary power converter are continuously energized, and the controller cannot affect their operation. The cathode heater and discharge supplies on the other hand are activated by the controller. The cathode heater supply requires one digital input for on / off control, and an analog input is required to set the value of the output current. In this control scheme, this is accomplished with a dedicated digital to analog converter to provide flexibility in the development process. Similarly, the discharge supply requires an analog input to set the output current. The discharge supply requires two digital inputs for on / off control of the power supply and the high voltage ignitor.

Cathode Activation Procedure

The cathode insert must be activated prior to use to ensure long life and efficient operation.[13] This involves a two-step heating process at low and high heater power settings with xenon flow, which is designed to drive off any impurities in the insert itself which could react deleteriously with the insert material. A flow diagram of this procedure appears in Figure 4. This procedure is normally a once only process, but in the event of difficulties in starting the cathode or suspected insert degradation, this routine can be called as an error recovery process. The SS DMS can interrupt this procedure at any time with the "contactor off" command.

Contactor On Procedure

This command ignites the PCU hollow cathode and maintains an anode-cathode discharge to facilitate the emission of electrons. A flow diagram of this procedure appears in Figure 5. Expellant flow is established, and the cathode heater is turned on at the nominal ignition setpoint for a predetermined time. The discharge supply is then turned on and develops its open circuit voltage. This open circuit voltage is generally enough to ignite the discharge, but in the event that ignition does not take place, a high voltage pulse ignitor is activated. When the discharge current exceeds 0.5 A, the pulse ignitor and the cathode heater supplies are turned off and the contactor begins steady state operation. The turn off of the pulse ignitor and cathode heater power supplies is accomplished through hard-wired logic and not affected by the controller. In the event of discharge extinction, the cathode heater and pulse ignitor will automatically energize, unless commanded off by the controller after the initial ignition. The discharge can be extinguished voluntarily by execution of the "contactor off" command. The electron emission process itself is self-regulating and requires no intervention or active control.

Contactor Off Procedure

The "contactor off" command returns the PEU to a standby state, regardless of the present status. The cathode heater supply, discharge supply, the pulse ignitor, and expellant flow are turned off. The controller continues to monitor all telemetry parameters and the command input bus for any change.

Error Detection and Recovery

The controller must detect and act on specific errors or failures to the plasma contactor system. These errors include, but are not limited to, loss of xenon expellant, cathode heater failure, and discharge ignition or steady state failure. In the instances of loss of expellant or cathode heater failure, there is nothing that can be done to reverse the problem. In these cases, the system reverts to the standby mode and must be replaced. However, in the event of an ignition failure, there are actions available to the controller to facilitate ignition. These include a repeat of the standard ignition process, a repeat of the activation process with standard ignition to follow, and a repeat of the ignition process with cathode activation and augmented heater power. If the failure persists, PCU is considered defective and is de-energized. In the event of contactor failure, the backup plasma contactor system will be activated.

POWER SUPPLY DESIGN

Control and Auxiliary Power Supplies

As previously stated, these power supplies are commercially available units which have been specifically designed for integration with the SS power system and are flight rated power supplies.

Cathode Heater

The cathode heater power supply is a pulse width modulated (PWM) push-pull converter with a switching frequency of 20 kHz. A schematic diagram of the power stage appears in Figure 6. The nominal output of the power supply is 64 W, but full rated power is 144 W. MOSFET switches with current ratings an order of magnitude higher than required for this application were used in an attempt to increase efficiency. The benefits are reduced conduction losses and improved reliability. A further attempt was made to reduce rectifier losses by using Schottky rectifiers which have a lower forward voltage drop than standard rectifiers. However, the long reverse recovery times increased the snubber requirements to the point that the losses were comparable to standard, ultra-fast recovery rectifiers. As a result, standard ultra-fast recovery rectifiers were chosen for the development effort. The design specifications for the cathode heater power supply are listed in Table III.

The cathode heater power supply provides a constant current output of 0 - 12 A into a load impedance of 0.3 to 1.2 Ω. A constant current output was selected to minimize heater power at turn on and allow for a gradual increase in heater power and temperature. A constant voltage power supply would develop maximum power into a cold heater and decrease in power output as the heater increased in temperature.

Discharge

A PWM controlled push-pull converter with a switching frequency of 20 kHz was also selected for the discharge power supply design. A schematic diagram of the power stage appears in Figure 7. The discharge supply has a nominal constant current output of 2 A into a load impedance of 5 to 14 Ω. The same techniques incorporated in the cathode heater supply to increase efficiency were also employed in the discharge supply. The requirements for a pulse ignition system were satisfied by the incorporation of a pulse ignition system similar to that used in arcjet power processors.[14] This pulse ignition system has the advantage of variable pulse amplitude and duration. The nominal pulse parameters are 900 V peak amplitude with duration of 8 μs. Work is ongoing to further refine these requirements and at least a 50 % reduction in pulse amplitude is expected based on related work with ion engine power processors.[15] The design specification for the discharge power supply are listed in Table IV.

RESISTIVE LOAD TESTING

Cathode Heater

The cathode heater power supply was operated into a resistive load to evaluate the efficiency of the power supply and the regulation characteristics. At the full rated power of 144 W (12 VDC @ 12 A), the efficiency was measured at 0.87. The efficiency at the nominal output of 64 W was 0.74. This drop in efficiency was due to the significant fractions of rectifier voltage drop vs. output voltage, and the control power, which remains constant vs. output power. As these fractions increase, they adversely effect the overall efficiency of the power supply. The line / load regulation characteristics were within specifications.

Discharge

The discharge power supply efficiency at a nominal output power of 30 W was measured at 0.64. The low efficiency was again due to the reasons outlined in the cathode heater section. All line and load regulation specifications were met successfully. The pulse ignitor was also tested with the discharge output open circuited. An oscillograph of the start pulse appears in Figure 8. The peak pulse amplitude was 950 V, and the duration was 8 μs.

PLASMA CONTACTOR INTEGRATION TESTS

A breadboard of the cathode heater and discharge power supplies was connected to a prototype PCU to evaluate the operation of the power supplies with the contactor and validate the pulse ignition technique. The PCU used closely resembled the engineering model design under development and was identical in function. Few problems were expected with the cathode heater supply since it had demonstrated stable operation into resistive loads over its entire operating range. However, validation of the discharge ignition procedures was necessary. Ignition of the discharge was successful with only the open circuit voltage of the discharge supply in most cases. However, when necessary, the pulse ignitor circuit successfully ignited the discharge. An oscillograph of steady state discharge operation appears in Figure 9. The operating conditions are 2 ADC @ 12.5 V. The steady state ripple in this case was approximately 200 mA or 10 %. Also of interest in the figure are the large switching spikes evident in the voltage trace. Preliminary EMI tests indicated that the combination of the ripple and switching noise caused significant EMI at the switching frequency and its harmonics. A redesign is underway to reduce the switching noise of the converter and to reduce the amount of ripple present in the output. Evaluation of reductions in the required ignition pulse amplitude and the discharge supply open circuit voltage are also presently in process.

CONCLUSIONS

A hollow cathode plasma contactor has been baselined as a charge control device for the Space Station (SS) to prevent deleterious interactions of coated structural components with the ambient plasma. Without this device, spacecraft floating potentials as large as -120 V with respect to the ambient plasma have been predicted due to the high voltage solar arrays and the negative ground configuration. NASA Lewis Research Center Work Package 4 has begun the development of a plasma contactor system to be contained in a standard Orbital Replacement Unit (ORU) avionics box. The plasma contactor system consists of a Power Electronics Unit (PEU), Expellant Management Unit (EMU), and the Plasma Contactor Unit (PCU). A breadboard PEU was designed, fabricated and integrated with a laboratory plasma contactor. The PEU contained a cathode heater and discharge power supply, which were required to operate the hollow cathode, a control and auxiliary power converter, EMU interface, command and telemetry interface, and a controller.

The control and auxiliary power converters selected were commercially available space qualified units. The cathode heater and discharge power supplies were designed and fabricated as part of the PEU development process. The cathode heater and discharge supplies utilized a push-pull topology with a switching frequency of 20 kHz and PWM control. A pulse ignition circuit derived from that used in arcjet power processors was incorporated in the discharge supply for discharge ignition.

An 8088 based microcontroller was selected to provide a flexible platform for controller development. A simple command/data interface was selected which incorporated a direct connection to SS MDM analog and digital I/O cards. This eliminated the hardware and software overhead associated with a 1553 serial interface. The controller accepted two-bit wide commands from a simulated MDM command interface and autonomously operated the controller based on these commands. Analog sensor data was also passed directly to the MDM, but critical parameters were processed by the controller for error trapping and health monitoring purposes.

The PEU was successfully integrated with a prototype PCU and demonstrated reliable ignition of the discharge in most cases using only the open circuit voltage of the discharge power supply. In the cases where the pulse ignitor was required, ignition was reliable. The test results indicate that a significant reduction in the ignitor pulse amplitude can be made. Several improvements to the design have also been identified which will improve the EMI characteristics of the PEU.

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Table I. PEU Commands

MSB	LSB	Command
0	0	Contactor Off (Standby)
0	1	Cathode Activation
1	0	Contactor On
1	1	Unused

Table II. Telemetry List

Parameter	Range
Cathode Heater Voltage	0 - 15 VDC
Cathode Heater Current	0 - 15 ADC
Discharge Voltage	0 - 30 VDC
Discharge Current	0 - 3.0 ADC
Electron Emission Current	0 - 10 ADC
+ 15 VDC Bus	0 - 20 VDC
- 15 VDC Bus	-20 - 0 VDC
28 VDC Bus	0 - 30 VDC
120 VDC Bus	0 - 150 VDC
Pressure #1	TBD
Pressure #2	TBD

Table III. Cathode Heater Power Supply Specifications

Input Voltage:	120 VDC nominal per SSP 30482
Output Voltage:	12 VDC maximum
Output Current:	12 A maximum
Regulation Mode:	Constant Current
Ripple:	< 15 %
Line/Load Regulation	< 1 %

Table IV. Discharge Power Supply Specifications

Input Voltage:	120 VDC nominal per SSP 30482
Output Voltage:	28 VDC maximum
Output Current:	2 A nominal
Regulation Mode:	Constant Current
Ripple:	< 10 %
Line/Load Regulation	< 1 %

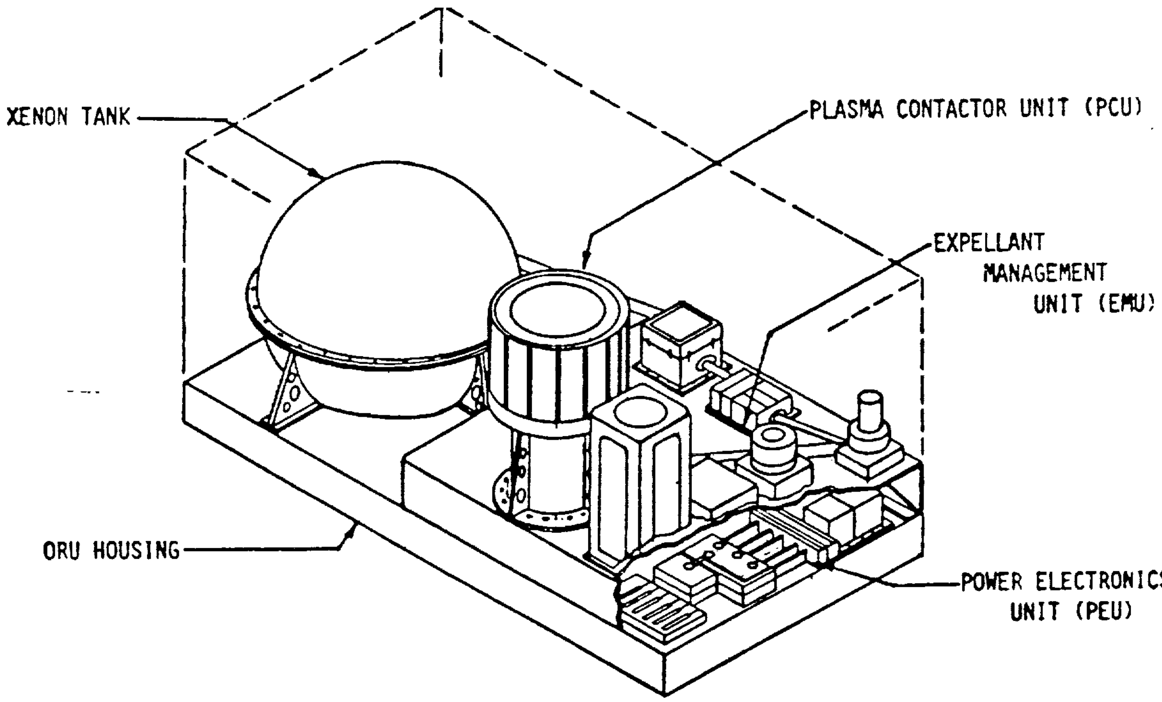

Figure 1. Simplified schematic of the plasma contactor in an Orbital Replacement Unit (ORU) avionics box

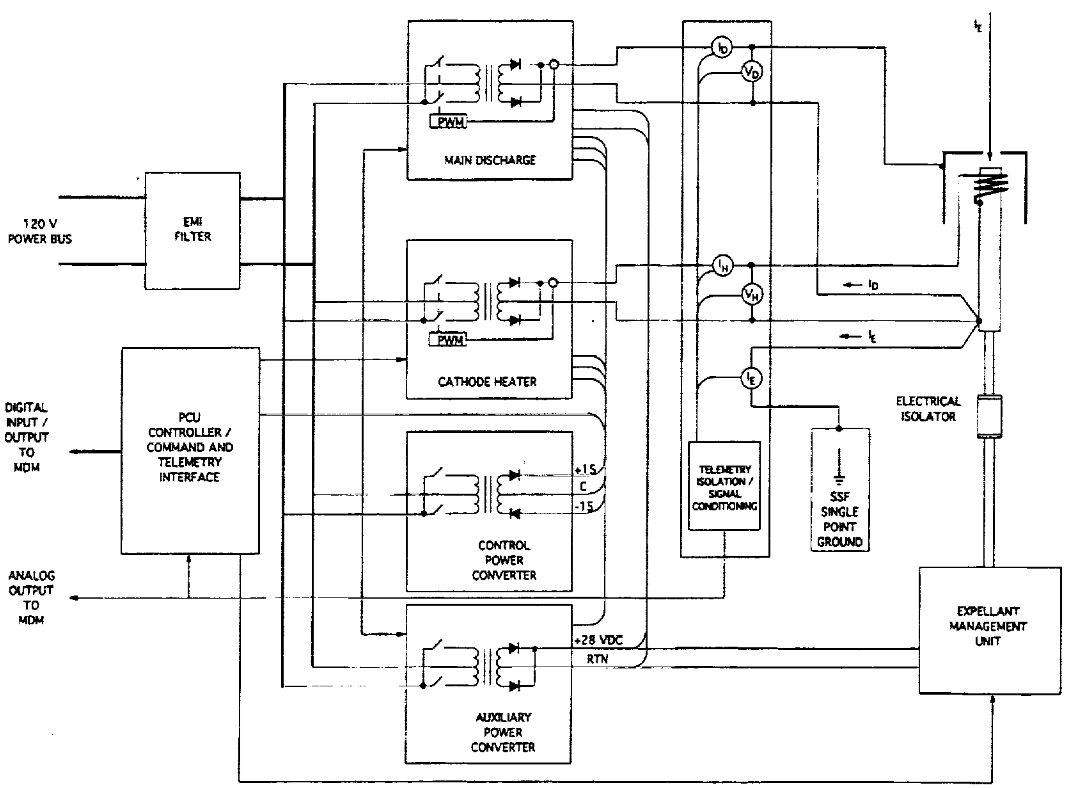

Figure 2. Power Electronics Unit (PEU) block diagram

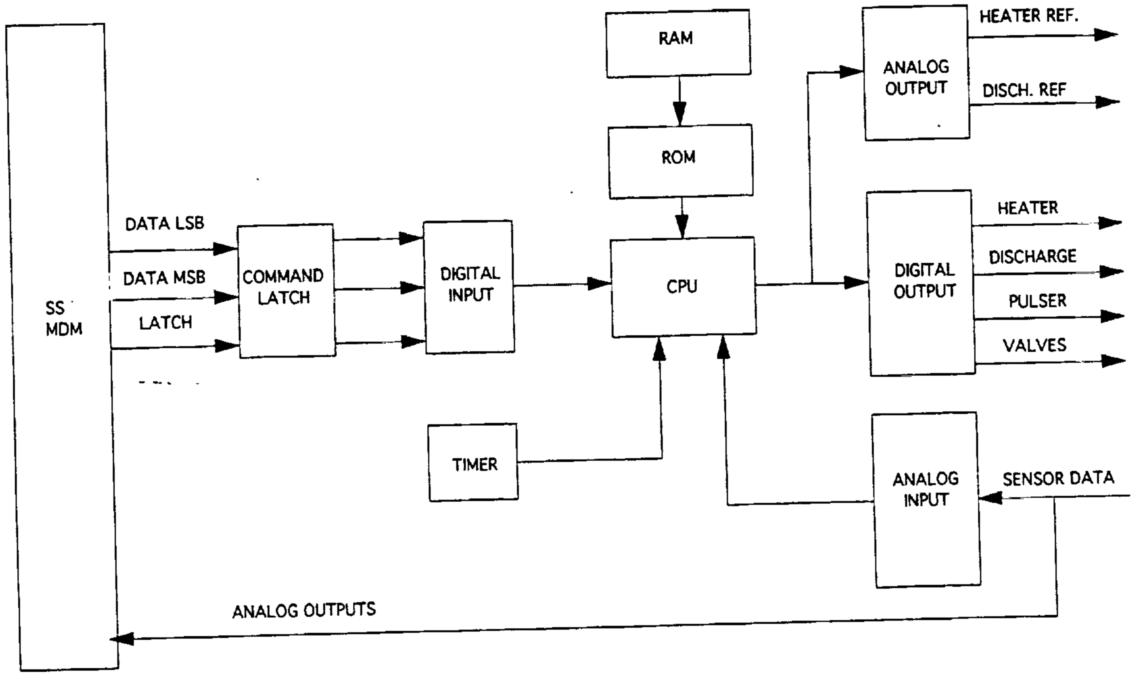

Figure 3. Controller block diagram

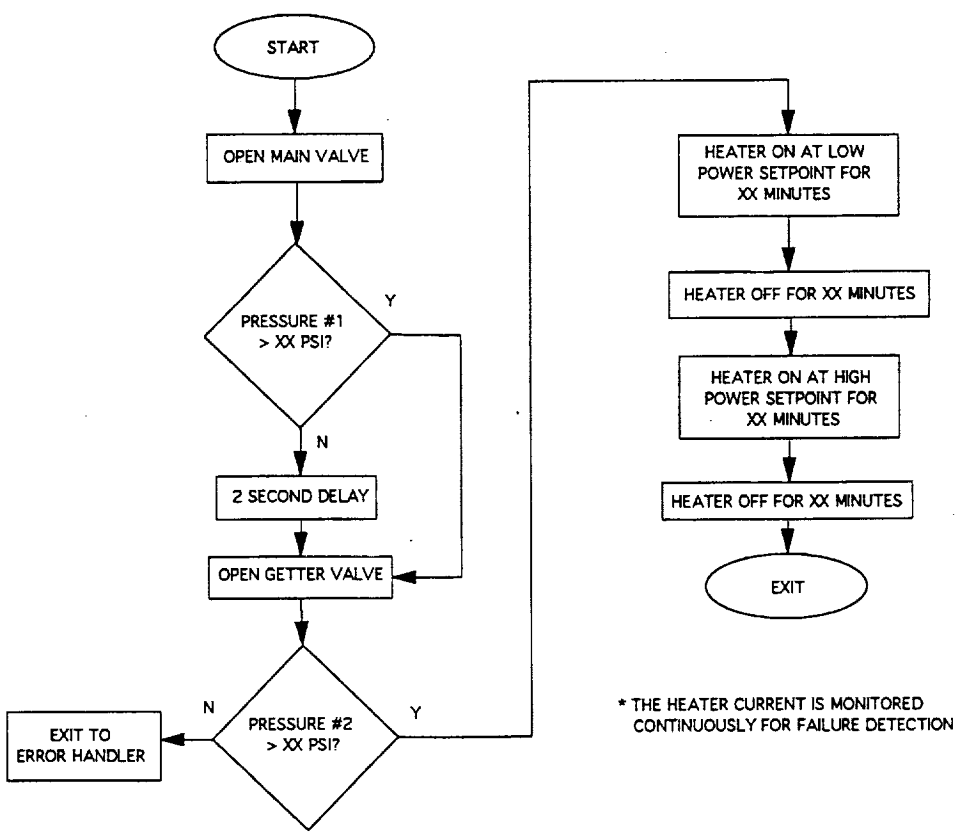

Figure 4. Cathode activation procedure flow diagram

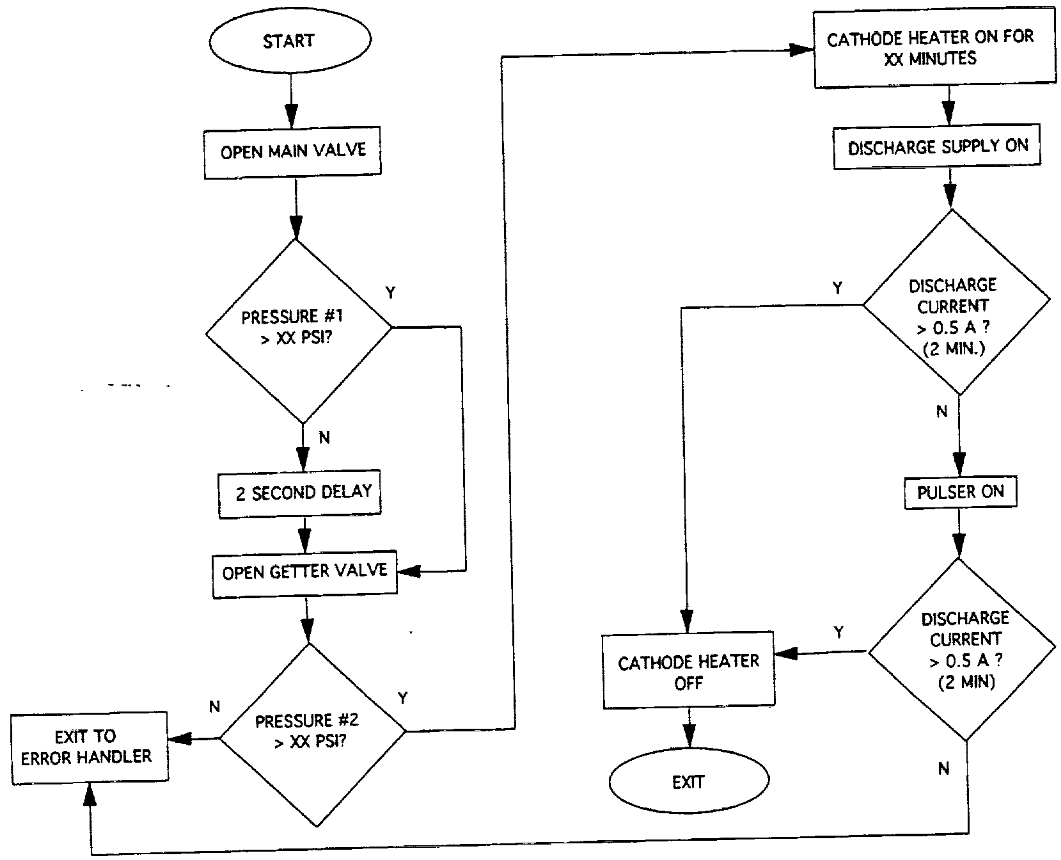

Figure 5. Contactor ON flow diagram

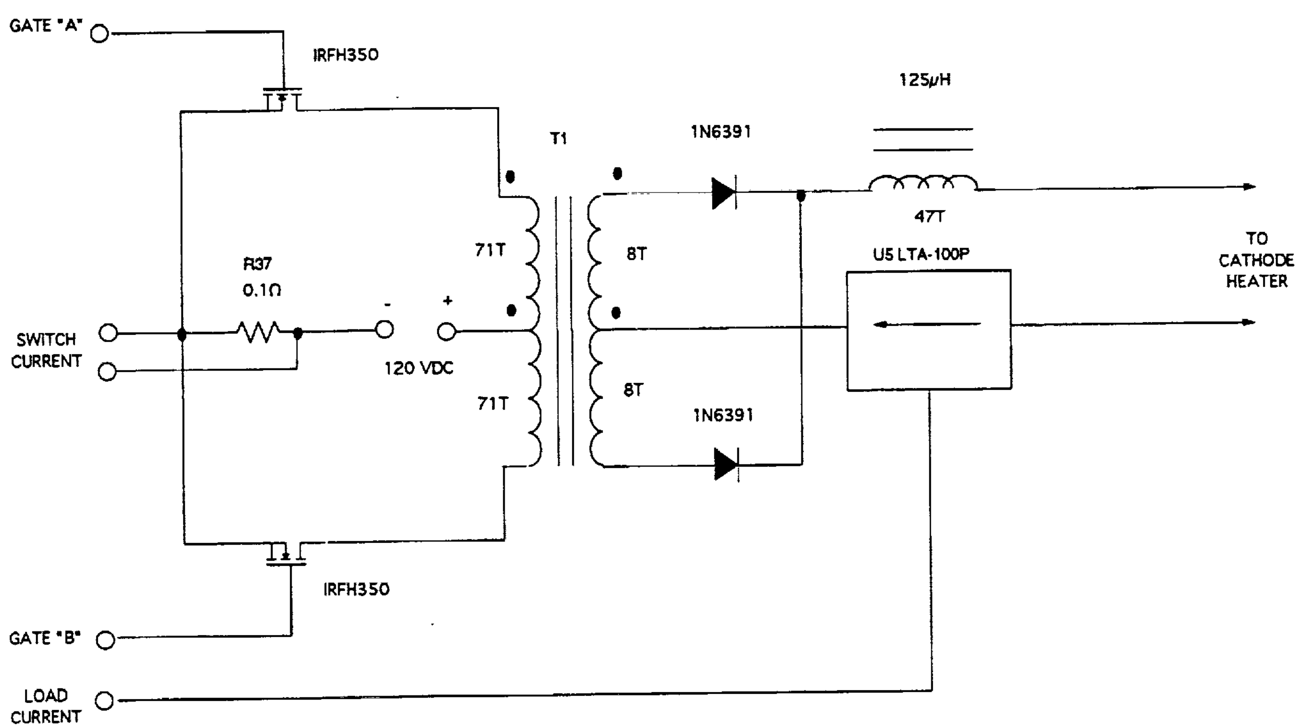

Figure 6. Cathode heater power stage schematic

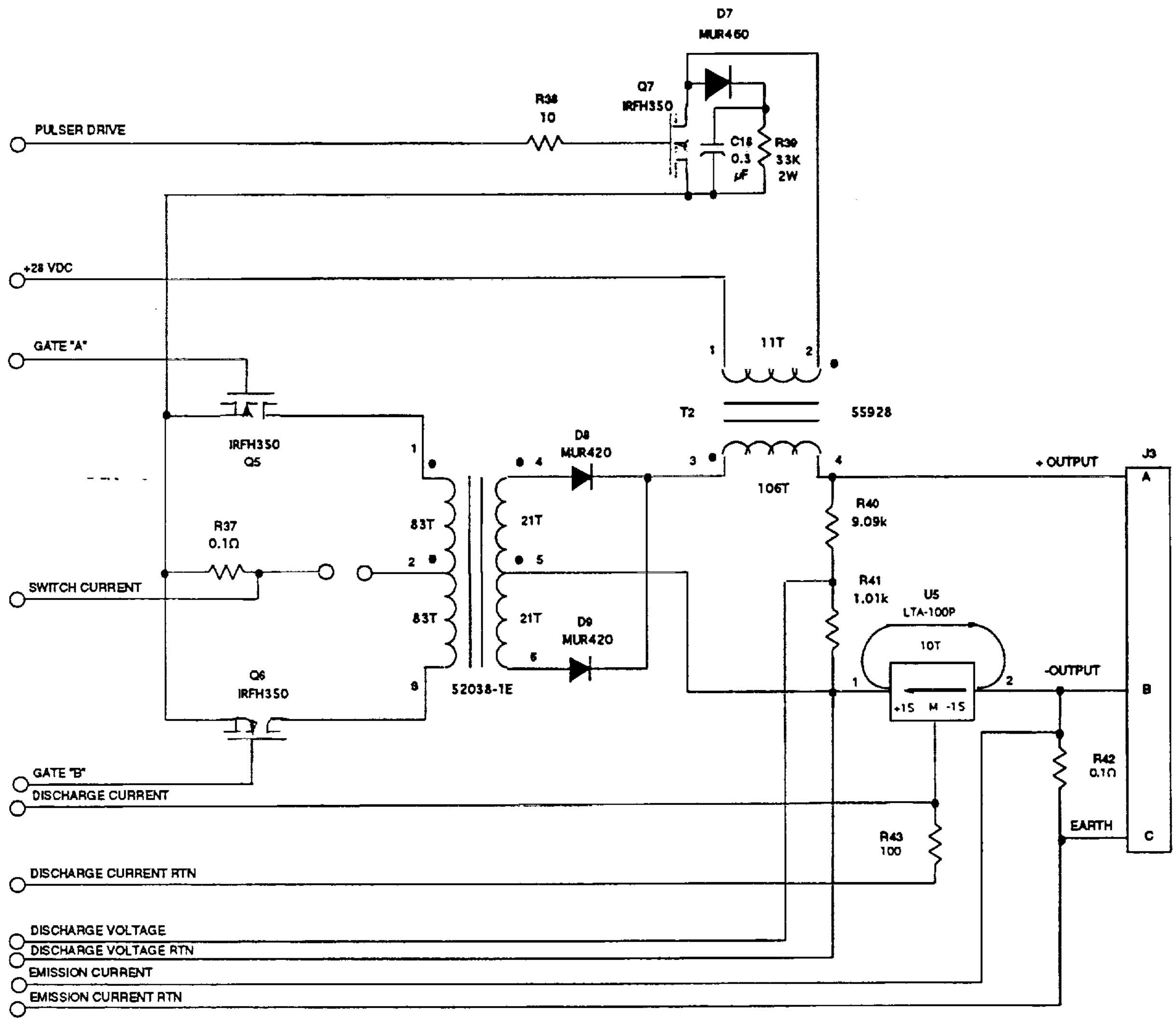

Figure 7. Discharge power stage schematic diagram

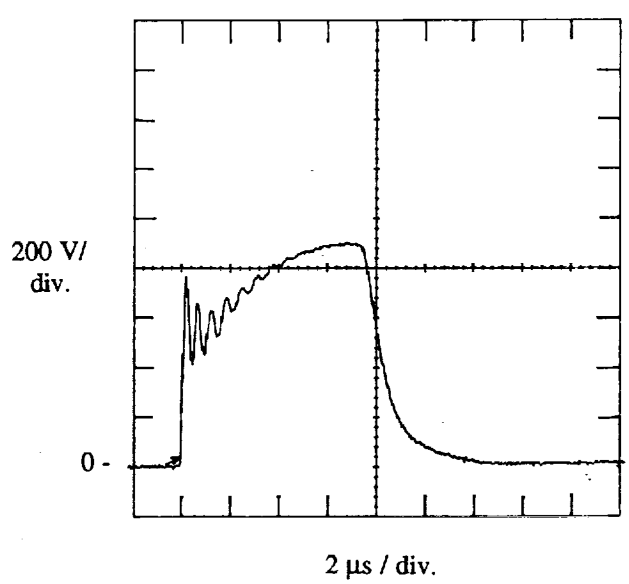

Figure 8. Pulse ignitor open circuit voltage

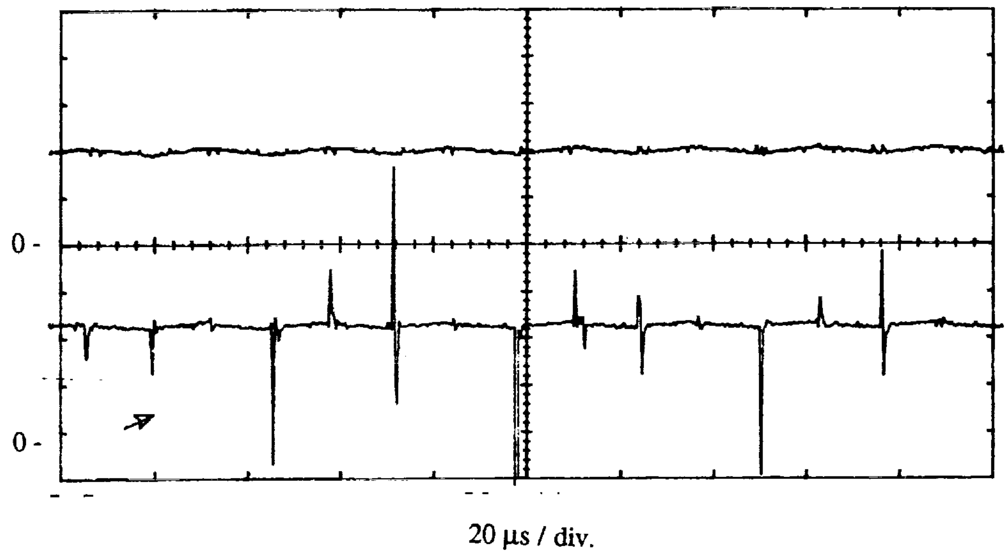

Figure 9. Steady state discharge voltage and current
Upper trace, Discharge Current, 1 A / div.
Lower trace, Discharge Voltage 5 V / div.

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11. SUPPLEMENTARY NOTES

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13. ABSTRACT *(Maximum 200 words)*

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